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1 February 1995; accepted 20 April 1995

The Heliospheric Magnetic Field Over the South Polar Region of the Sun

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Magnetic field measurements from the Ulysses space mission over the south polar regions "of the sun showed that the structure and properties of the three-dimensional heliosphere were determined by the fast solar wind flow and magnetic fields from the large coronal holes in the polar regions of the sun. This conclusion applies at the current, minimum phase of the 11-year solar activity cycle. Unexpectedly, the radial component of the magnetic field was independent of latitude. The high-latitude magnetic field deviated significantly from the expected Parker geometry, probably because of large amplitude transverse fluctuations. Low-frequency fluctuations had a high level of variance. The rate of occurrence of discontinuities also increased significantly at high latitudes.

The characterization of the intrinsicallv three-dimensional nature of the heliosphere the prime objective of the Ulysses space mission (1). The asymmetric and time-dependent solar corona, combined with the rotation of the sLm, makes high-latitude phenomena different from those seen near ecliptic plane. We discuss observations by the magnetometer on board the spacecraft (2) on the structure and characteristic features of the magnetic fields the southern polar region of the sun. ...etic fields in the heliosphere have origin in the outer atmosphere of the the solar corona. The corona consists highly ionized solar material at temperatures in excess of 1.5 x 10^6 K, threaded by magnetic field lines rooted in the photo-... A fraction of the mechanical energy ...ng ftom the solar convection zone is ...rmed, by as yet not **fully** understood ...es, into heat in the corona. The ... is fundamentally unstable: Part of ...onal plasma is accelerated to supersonic speeds and escapes into space to form ... wind. The origin of the solar wind ... well understood, but is related to the ...ale structure of the magnetic field ... the heating and dynamics of the ... space, the solar wind plasma is ... perfect electrical conductor, and ... it drags out the magnetic field embedded in it. The large-scale structure ... corona undergoes major changes ... the 11-year solar activity cycle.

During solar minimum, large areas in the polar regions of the corona, the polar coronal holes, have an open magnetic field line structure. Coronal holes that extend toward the equator in the declining phase of the solar cycle have been identified as the sources of fast solar wind streams, with speeds up to 800 km/s.

The strength of the heliospheric magnetic field observed by the Ulysses magnetometer from the jovian encounter near the ecliptic to the highest southern latitude in the orbit at 80.2° showed the transition from low-latitude to high-latitude conditions (Fig. 1). During the low-latitude to mid-latitude part of the orbit, slow solar wind associated with coronal regions close to the heliospheric current sheet (the extension of the heliomagnetic equator into interplanetary space) was periodic ally compressed, with a period approximately that of the solar rotation rate, by high-speed flows from the developing southern polar coronal hole (3). This led to the train of periodic magnetic field enhancements in the corotating interaction regions (CIRs). The CIRS were bounded by forward and reverse shock waves. During this interval, the average direction of the heliospheric magnetic field alternated between the two magnetic polarities associated with the northern and southern solar hemispheres. This alternating field divides the solar rotation periods into the well-known two-sector structure representative of this phase of the solar cycle. However, throughout rhis interval, the sector structure showed an apparent eastward drift, corresponding to a recurrence rate of the coronal structures responsible for the CIRs slower than the solar rotation period at the equator. The likely cause of this effect has been identified as the eastward drift of rhe nonaxisymrnetric terms of the solar magnetic field (4), **a** diagnostic of the evolution of solar magnetism from solar maximum to minimum activity. The last crossing of the heliospheric current sheet was observed at a heliolatitude of 30° south (5). Signatures of CIRs nevertheless continued to 45° south. Forward shock waves associated with CIRS were last observed at 35°, while, contrary to expectations, reverse shocks became relatively more frequent and persisted to about 45" south (6). The explanation proposed for this observation is based on a three-dimensional model of the development of CIRS at mid- to high latitudes (7). The format**ion** of shock waves, their topology and their propagation at the high-latitude edges of CIRS remains to be fully explained.

Well after the disappearance, at mid-latitudes, of shock waves caused by CIRs, Ulysses observed a series of shock waves at high latitudes (Table 1). Five of the seven shock waves were apparently associated

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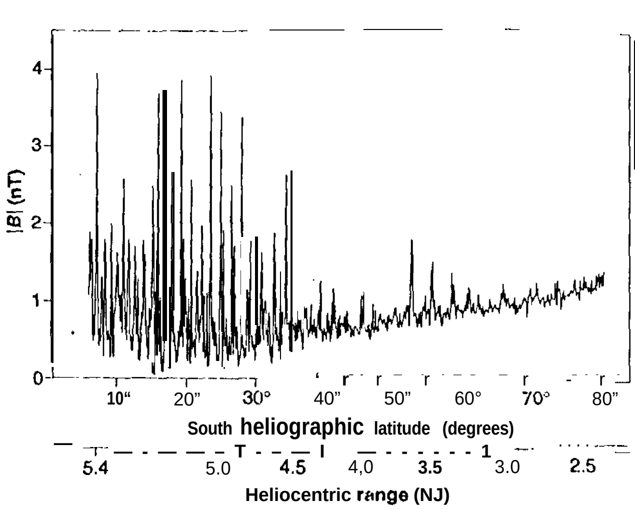

Fig. 1. Hourly averages of the magnetic" field magnitude measured along the Ulysses orbit, as a function of heliolatitude and heliocentric distance,

with the new class of coronal mass ejections, with a larger internal pressure than that of the ambient solar wind, first identified in the Ulysses data (8). Five (not the same set) were reverse shocks, maintaining **the trend** from the mid-latitude observations of a prevalence of reverse shocks at high latitudes. The shocks were generally weak. in one case, when the solar wind plasma showed a shock-like change on a timescale of tens of minutes, but without a clear shock jump being identified by the magnetometer on time scales of tens of seconds, the discrepancy could be due to the dissipation of the shock waves some time before the observations but nevertheless leaving a remnant of a signature in the solar wind (9).

Variations in magnetic field strength are a good diagnostic of dynamic processes in the solar wind. However, because of this sensitivity to compressional effects, which are evolving as a function of time (and heliocentric distance), the magnitude of the magnetic field cannot be easily interpreted

Table 1. High-latitude shock waves observed by Ulysses in the uniform, high-speed solar wind from the southern polar coronal hole

Date	Time (UT)	Type	Assoc.
12 February 1994	20:10	R'	**CME**
26 February 1994	13:14	F	**CME**
1 March 1994	15:42	R	**CME**
10 March 1994	12:57	R	CIR‡
3 April 1994	15:23	R	CIR‡
20 April 1994	09:00	F†	**CME**
23 April **1994**	10:39	R	**CME**

'Without clear solar wind signature. Without clear magnetic field signature. ‡Apparently compressive, recurrent structures.

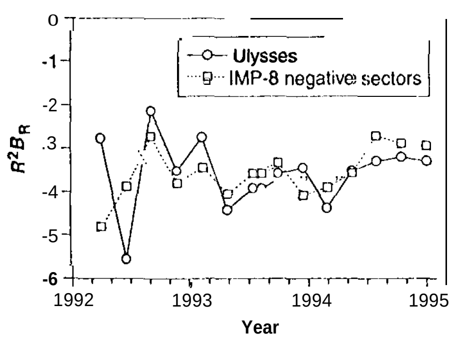

Fig. 2. The radial component of the magnetic field measured by Ulysses over a heliolatitude range of 7° to 80° south and normalized to 1 AU, compared to the radial component measured at 1 AU by IMP-8 (courtesy of R, Lepping). Only negative polarity data from IMP-8 have been used to provide a comparison with the southern magnetic polarity observations by Ulysses, The close tracking of the two curves clearly shows that the radial component of the heliospheric magnetic field is independent of heliolatitude.

in terms of the solar field strength. Compressional effects mostly affect the components of the magnetic field vector transverse to the radial direction; therefore, the latitude dependence of the solar magnetic field is best studied using the radial component, B_R, of the heliospheric field observed by Ulysses. The agreement between the value of this component measured along the Ulysses orbit, normalized to 1 AU, and the same component of the field measured at the same time in the ecliptic plane at 1 AU (Fig. 2) demonstrates that the magnetic field over the coronal hole is independent of heliolatitude (*10*).

This conclusion is in contradiction with models predicting the behavior of the heliospheric magnetic field as a function of latitude (at solar minimum activity), based on extrapolations of solar surface magnetic fields. These models predict a significant increase, up to a factor of 3, over the polar region as a result of the dominance of the solar magnetic dipole term which, at solar minimum, is approximately aligned with the solar rotation axis. The implication of the discrepancy between the models and the observations is that the assumptions built into the models as to how solar magnetic fields are distributed by dynamic processes in the corona, in the source regions of the solar wind, need to be revised. In particular, models in which the magnetic fields are current-free (the so-called potential models) between the photosphere and a concentric spherical surface in the corona (the source surface) predict a stronger, more dipole-like field at Ulysses than observed.

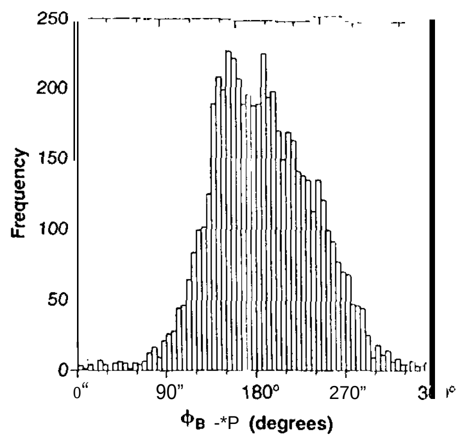

Fig. 3. Hourly averages of the azimuthal angle of the magnetic field measured by Ulysses (all data for latitudes **>60°),** referenced to the expected Parker direction, calculated using the measured values of the solar wind velocity (by courtesy of J. Phillips). The southern hemisphere magnetic polarity of the sun is "toward" in the current solar cycle, hence the value of the expected Parker direction is 180° in the spherical coordinate system corotating with the sun and centered on the observer.

Even modifications of such models, takin into account the contribution of the helio spheric current sheet, predict a latitude dependent field, in particular, a significant increase in the radial component of th magnetic field at Ulysses (*11*). In the ligh of the observational results, it is clear that further effect, that of significantly strong magnetic stresses in the polar regions, nee to be taken into account. Although coron images at solar minimum often show ev dence of a divergence of the magnetic fiel lines near the sun, it has not been clear ho strongly this divergence affects the sol wind flow from the polar coronal holes an as a consequence, how solar wind from th polar regions can reach down to mid-lat tudes or even to low heliospheric latitud Ulysses magnetic field results provide t basis for a quantitative estimate of t large-scale divergence of the flow, which crucial **to** solar wind models.

Parker's original model for the heli spheric magnetic field (*12*) was derived u ing a uniform solar wind speed and pure radial magnetic fields at the sun. This mo el, while modified extensively by the d covery of the stream structure of the sol wind near the ecliptic plane, has proved be a useful framework to describe the av age orientation of the interplanetary m netic field. In the solar equatorial plane, t rotation of the sun twists the magne field, on average, into the form of Archimedean spiral. Away from the equ torial plane, field lines originating at a g en heliolatitude are draped on the surface a cone with a half-angle equal to the cola tude of the field line. Earlier observati by spacecraft close to the ecliptic pla

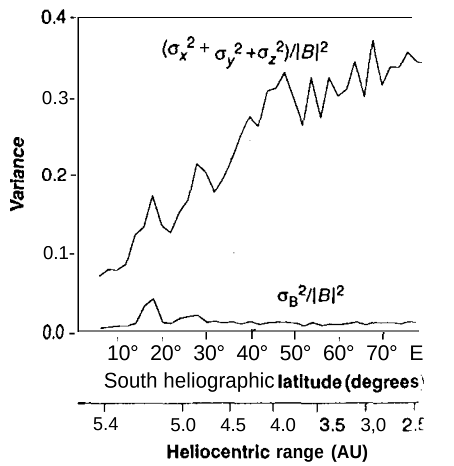

Fig. 4. Latitude dependence of the normali variance in the magnetic field magnitude, σ $|B|^2$, and of the sum of the variances of the m netic field components $(\sigma_x^2 + \sigma_y^2 + \sigma_z^2)/|B|^2$. variances have been calculated using the full r olution (1 or 2s per vector) data in hourly inter and the resulting hourly variance values have t been averaged over 27-day intervals

showed that (13), on average, the direction of the magnetic field vectors is that derived from Parker's model, as also confirmed by Ulysses (14). However, in-ecliptic data from other spacecraft imply a possible over-winding of the spiral (15); this may be related to effects of the solar cycle. Ulysses observations up to 60° south latitude (16) showed that, in this latitude range, the most probable orientation of the out-of-ecliptic magnetic field remains to a good approximation the Parker direction. However, the distribution around the most probable direction showed, already at low and medium latitudes, an asymmetry, indicating that, on average, magnetic field lines have a tendency to be less rather than more tightly wound than expected on the basis of Parker's model. The complete Ulysses data set for heliolatitudes greater than 60° (Fig. 3) showed that at the highest latitudes explored by Ulysses, neither the most probable value of the field direction nor the average direction follow the expected Parker model. If hourly averages are used, as in Fig. 3, the most probable value corresponds to field lines that are more, rather than less, tightly wound, and the distribution retains the same asymmetry as already seen at lower latitudes. However, the average direction is sensitive to the averaging period used, and can indicate accordingly a more or less tightly wound configuration.

This deviation at high latitudes from the Parker geometry, we suspect, is the result of the large-amplitude directional fluctuations, particularly at longer wavelengths that, being mostly transverse to the field, introduce a bias in the azimuthal direction of the magnetic field. There is little doubt that the structure of the heliospheric field is more complex than that anticipated on the basis of the Parker model. This effect has been at least qualitatively foreseen, on the basis of the assumed random motion of the footprints of field lines in the photosphere (17).

The level and nature of fluctuations in magnetic field strength and, more importantly, in direction, in the polar heliosphere affect the access of galactic cosmic rays above the solar poles and provide information, albeit indirectly, on conditions in the solar corona. These fluctuations can be quantified in different ways. Fluctuations at the longer wavelengths have been characterized by the total variance in the components of the magnetic field, compared to the variance in the magnitude of the field vector (Fig. 4). The significantly increased level of variance in the components at high latitudes indicates that the direction of the magnetic field is much more variable than its strength. The unexpectedly strong residual modulation of cosmic rays over the polar regions observed by Ulysses (18) is a direct consequence of the increased level of directional fluctuations in the magnetic field. The longer period fluctuations, with a power spectral exponent close to -1, were highly Alfvénic (19). Fluctuations in the transverse components of the magnetic field vector and the corresponding transverse components of the solar wind velocity vector were in phase. These observations showed that with the transverse components of the magnetic field dominated by large amplitude fluctuations and a consistently sunward-pointing radial component (Fig. 5), the fluctuations propagated outward in the solar wind frame, in a manner fully consistent with their origin close to the sun.

Structure function analysis has been used previously to study interplanetary fluctuations near the ecliptic plane (20). The implied power spectral exponent of the magnetic field fluctuations can be deduced from such structure function analysis (21). Two different spectral regimes were observed by Ulysses. Fluctuations at high frequencies, above about 10^{-3} Hz, are the result of small-scale, intermittent turbulence generated in the solar wind. The power spectral exponent of these turbulent fluctuations is close to the Kolmogorov value of $-5/3$, similar to that which has been found near the ecliptic plane (22), although a better match to the observations is achieved by higher order MHD models (23). At low frequencies, below about 10^{-4} Hz, the power spectral exponent of fluctuations is close to -1. This regime appears to be similar to that observed in the ecliptic at 0.3 AU by the Helios spacecraft, in high-speed solar wind streams (24). However, in the ecliptic, these fluctuations became effectively masked between 0.3 and 1 AU by the development of dynamic interaction regions between fast and slow solar wind flows. At high latitudes, in the relatively uniform solar wind flows from the polar coronal hole, these fluctuations were observed by Ulysses out to beyond 4 AU. This indicates that fluctuations that originate much closer to the sun, in the acceleration region of the solar wind, are less likely to decay in the uniform polar solar wind flows. The long wavelength fluctuations therefore provide a probe into conditions in the co-

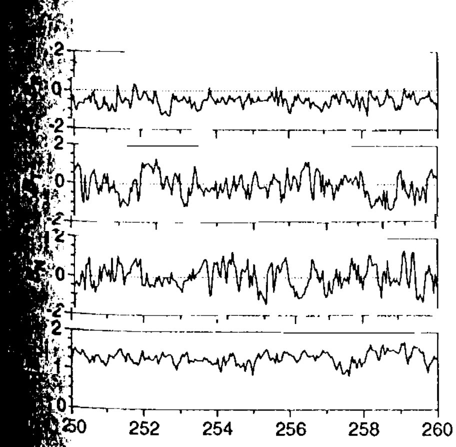

Fig. 5. Hourly averages of the magnetic field magnitude and its three components over an interval of 10 days around the time of the highest southern latitude reached by Ulysses (7 September to 17 September). Although the magnitude and the radial component of the field are relatively smooth, the two transverse components show large amplitude fluctuations. This figure illustrates the prevalence of long wavelength transverse, mostly Alfvénic fluctuations in the magnetic field at high latitudes.

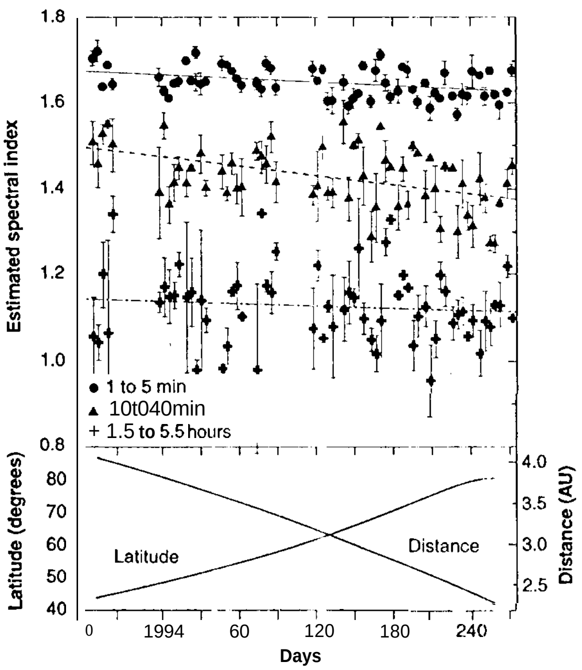

Fig. 6. (Top) Power spectral indices of nearly 1 year of Ulysses magnetic field data taken within polar solar wind flows, indicating evolution of the fluctuations with radial distance. **(Bottom)** Heliographic latitude and distance of the spacecraft. The power spectral indices are shown for three frequency ranges, together with least squares straight line fits to the data. The 1- to 5-min scale (circles) is within the inertial turbulent regime, where the power spectral index is near $-5/3$. At hourly scales, (crosses) the power spectral index is near -1; this population of fluctuations is unlikely to have changed since leaving the upper corona. The intermediate scale of 10 to 40 min (triangles), however, changes significantly over this time interval. The power spectral index alters to higher values with heliocentric distance, indicating an evolution of the fluctuations on this scale toward fully developed turbulence.

rona and, in particular, into the dynamic processes and structures that are associated with the acceleration of the solar wind.

The transition between the two different regimes varied along the orbit of Ulysses (Fig. 6): Closer to the sun, at higher latitudes, the transition between unevolved fluctuations and turbulence occurs at higher frequencies, consistent with the slow evolution of fluctuations with heliocentric distance. In this interpretation, a population of fluctuations with an essentially $1/f$ spectrum close to the sun evolves, through the intermed iary of small velocity fluctuations in the solar wind, toward a fully developed turbulence with a power spectral exponent of –5/3. This model is likely to be somewhat simplistic, as shown by the more detailed study based on structure function analysis, that includes correlations higher than second order (2 *1*). Although the evolution and mix of the fluctuations observed in the fast solar wind flows at polar latitudes is thus significantly different from that near the ecliptic plane, the interpretation of the observations in terms of detailed processes on the microscales and mesoscales of the solar wind remains m be completed.

Fluctuations in the magnetic field in any case cannot be fully described in terms of conventional spectrum analysis. While structure function analysis provides a more complete understanding into the statistical nature of the fluctuations, the study of discontinuities provides a complementary approach into aspects of the microstructure of the polar flows. The rate of occurrence of discontinuities, as measured using criteria defined previously for in-ecliptic measurement, has been found to increase significantly (up to 100 to 200 per day) in the high-speed polar solar wind (25), when compared to rates found near the ecliptic. The presence of discontinuities appears to be strongly correlated with the presence of Alfvén waves. When individual examples of discontinuities arc examined, it is found that the discontinuity is part of the Alfvén pulse train, and corresponds to the phase-steepened edge of the wave.

A feature of the microscale structure is the frequent occurrence of nulls (or holes) in the magnetic field (26). These events, in which the strength of the magnetic field drops to a value close to zero (without a change in the direction of the field), are of short duration (of the order of tens of seconds) and represent a significantly different state of the solar wind plasma. Although such events had **been** noted in the ecliptic (27), their rate of occurrence is significantly enhanced at high latitudes. Their relation to the mirror-mode instability first identified in the Earth's magnetosheath (28) isat present unclear, as is their frequent association with tangential discontinuities. There is evidence of plasma (Langmuir) wave activity associated with the magnetic holes (29), possibly caused by streaming energetic electrons. Another feature of the short time-scale magnetic field observations is rhc presence of current-sheet-like features, characterized by dropouts in the magnitude of the magnetic field, associated with sharp deflections of the field direction. Taken together, the collection of small-scale phenomena in the high-speed and relatively uniform solar wind characteristic of the polar region represent new classes of plasma processes for use as diagnostics of coronal and heliospheric processes.

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30. Support for the magnetic field investigatic Ulysses at Imperial College is provided b U.K. Particle Physics and Astronomy Res Council, and, at the Jet Propulsion Laborato the National Aeronautics and Space Admi tion. We thank N. Murphy, J. Feynman, A maikin, J. Wolf, C. M. Ho, G. Erdös, anc Gonzales-Esparza for contributions to the analysis. We also thank J. Phillips, D. McC and M. Neugebauer for providing Ulysses wind data and R. Lepping who provided the I magnetic field data used in Fig. 2.

10 February 1995; accepted 17 April 1995

Over the Southern Solar Pole: Low-Energy Interplanetary Charged Particles

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The heliosphere instrument for spectrum, composition, and anisotropy (HISCALE) corded the fluxes of low-energy ions and electrons (>50 kiloelectron volts) when Ulys crossed the southern solar polar region and revealed that the large-scale structure of heliosphere to at least --75° was significantly influenced by the near-equatorial he spheric current sheet. Electrons in particular were accelerated by the current she produced and poleward-propagating interplanetary reverse shock at helioradii far fr the Ulysses location. At heliolatitudes higher than - -75° on the Ulysses ascent to pole and -- 50° on the descent, small, less regular enhancements of the lowest ene electron fluxes were measured whose relations to the current sheet were less clear. 1 anomalous component of low-energy (-2 to 5 megaelectron volts per nucleon) oxy flux at the highest heliolatitudes was found to be -10-8 [per square centimeter persec per steradian (per kiloelectronvolt per nucleon)]; the anomalous Ne/O ratio was ~0.

The HISCALE investigation (I) on the Ulysses spacecraft provided three-dimensional measurements of the distribution is of low-energy charged particles (electrons and ions with energies between 50 keV and 5 MeV) in the heliosphere. These low-energy particles are accelerated from lower ene plasmas by magnetohydrodynamic proces in the solar corona and photosphere, as w as in interplanetary shock waves. SCALE also measured the composition the low-energy [$E >$ 0.5 MeV per nucl